To appear in ApJ Letters

Magnetic fields at the periphery of UCH II regions from carbon recombination line observations

D. Anish Roshi[1]

ABSTRACT

Several indirect evidences indicate a magnetic origin for the non-thermal width of spectral lines observed toward molecular clouds. In this letter, I suggest that the origin of the non-thermal width of carbon recombination lines (CRLs) observed from photo-dissociation regions (PDRs) near ultra-compact H II regions is magnetic and that the magnitude of the line width is an estimate of the Alfv*é*n speed. The magnetic field strengths estimated based on this suggestion compare well with those measured toward molecular clouds with densities similar to PDR densities. I conclude that multi-frequency CRL observations have the potential to form a new tool to determine the field strength near star forming regions.

Subject headings: ISM:magnetic fields – radio lines:ISM – ISM:lines and bands – ISM:molecules – MHD – H II regions

1. Introduction

Observations of high-density molecular line tracers toward ultra-compact H II regions (UCHs) reveal that these H II regions are embedded in dense ($\gtrsim 10^5$ cm^{-3}) molecular clouds (eg. Churchwell, Walmsley & Cesaroni 1990; Churchwell 2002 and references there in). Far ultra-violet (FUV; 6 to 13.6 eV) radiation from massive stars within the UCHs heats the dense molecular material in this interface, producing a Photo Dissociation Region (PDR) (see Hollenbach & Tielens 1997). Carbon recombination lines (CRLs) from such regions have been detected toward a large number of UCHs, establishing the presence of dense PDRs near most UCHs (Roshi et al. 2005a).

[1]Raman Research Institute, Sadashivanagar, Bangalore 560 080, India; anish@rri.res.in

The observed width of the CRLs from PDRs associated with UCHs is typically between 4 and 8 km s^{-1}. The gas temperature in the PDR, obtained by non-LTE modeling of CRL emission at multiple frequencies, is in the range 200 to 1000 K (Roshi et al. 2005b; Garay et al. 1998; Natta, Walmsley & Tielens 1994). Thus the expected thermal contribution to the line width is at least a factor of two smaller than the observed width (see Fig. 1). This larger observed width indicates that the CRL width is dominated by supersonic motions. In fact, a similar situation exists in molecular clouds. It has long been recognized that the observed width of spectral lines from molecular clouds have a non-thermal component and this component is often supersonic (eg. Barrett, Meeks and Weinreb 1964). The origin of the non-thermal component of the line width is now attributed to either "turbulence" (Morris et al. 1974; Zuckerman & Evans 1974) or Alfv́en waves (Arons & Max 1975; Mouschovias 1975; see also Shu, Adams & Lizano 1987 and references there in).

Detailed theoretical models for both "turbulence" and Alfv́en waves in molecular clouds are yet to be worked out. But "turbulence" without any magnetic field is a less plausible proposition since observations demand supersonic turbulence and the rapid dissipation in shocks cannot sustain such turbulent motions to time scales larger than the free-fall time (eg. Shu et al. 1987). The decay of Alfv́en waves are slow compared to supersonic turbulence though simulations show that they may also need a driving mechanism (MacLow 2003). Thus Alfv́en waves appear to be a more tenable explanation for the observed line widths (Arons & Max 1975; Mouschovias 1975).

Observational data also seem to indirectly support the magnetic origin of the line width. Analysis of the width of spectral lines observed toward molecular clouds shows power-law relationships between the non-thermal component of the velocity dispersion, the cloud size, density and the magnetic field strength (Larson 1981; Troland & Heiles 1986; Myers & Goodman 1988a, 1988b; Mouschovias & Psaltis 1995; Crutcher 1999). These relationships are expected in self-gravitating, magnetically supported clouds since the Alfv́en waves in such clouds affect the observed line width (Mouschovias 1987; Myers & Goodman 1988a, 1998b).

In this letter, I use the observed non-thermal widths of CRLs to estimate the magnetic field strength in PDRs near UCHs. The field strength is estimated by assuming that the non-thermal velocity dispersion of carbon lines give an estimate of the Alfv́en speed in the PDR. This assumption is based on a comparative study of the characteristics exhibited by the CRL and molecular line data. The data and the comparative study are presented in Sections 2 and 3 respectively. The magnetic field strength is obtained by combining the velocity dispersion of CRL and the density derived from modeling carbon line emission (see Section 4). To our knowledge the only attempt to compute the magnetic field using CRLs was made by Vallee (1989), where he had applied a model for shocks at the edge of molecular clouds to deduce the field strength.

2. Carbon recombination line data

For the present analysis I use CRL data toward UCHs since the PDR thickness is small in these cases and therefore large scale motions (such as outflows) may not affect the line width (see Section 5). Table. 1 summarizes the CRL data and results obtained from modeling this data toward 14 UCHs. Listed are the source name, observed CRL transition, FWHM of CRLs[1], PDR gas temperature, carbon ion density, number density of hydrogen atoms in the PDR, line-of-sight extent of the PDR ($L_{\|}$) and the estimated magnetic field strength (see Section 4).

The quality of the CRL data obtained toward all 14 sources is good; the uncertainties are mostly in the parameters derived by modeling line emission. The frequencies of the selected CRLs are below $\sim$ 15 GHz. As inferred from modeling, carbon line emission is dominated by stimulated emission at these frequencies (Natta et al. 1994; Roshi et al. 2005a). The data toward the first 7 sources in Table 1 were obtained using interferometric observations. The line widths for the first six sources were obtained from profiles averaged over regions where lines were detected. The properties of the PDR toward W3A were not well constrained; I have taken representative model parameters from Kantharia, Anantharamaiah & Goss (1998). Data toward the remaining 7 sources were obtained with the Arecibo telescope. Modeling of CRL emission toward these sources was limited by: (a)poor angular resolution, (b)flux density calibration error and (c) detection of line only near 9 GHz. Thus modeling this data set has given only constraints on the physical properties of the PDR. The PDR gas temperature of 500 K for the Arecibo sources and W48A, W49G and W49J listed in Table 1 is a representative value. The carbon ion density and $L_{\|}$ obtained from modeling depend non-linearly on the gas temperature. Converting the ion density to neutral density is somewhat uncertain due to the unknown depletion factor and the fraction of molecular hydrogen in the CRL forming region. Based on the examination of the models for W48A and our experience in modeling other CRL data set (Roshi et al. 2005; Roshi et al. 2006), it is expected that the values for temperature in Table 1 can vary by a factor of 2 and the values for neutral density and $L_{\|}$ can vary by a factor of 4. The model parameters are derived using a simplified geometry of plane parallel PDR slabs. A comparison of the PDR

[1]The relationship $\Delta V = \sqrt{8ln(2)}\ \sigma_{NT}$ is used in this paper to relate the FWHM line width ΔV to the dispersion σ_{NT} for a Gaussian line model

properties obtained from such models toward W48A with those obtained from models which take into account the photo and chemical processes in the PDR shows that detailed modeling gives values within the factors quoted above (Jeyakumar et al. 2007 in preparation).

3. Alfv́en speed in molecular clouds and non-thermal width of carbon recombination lines

Molecular clouds are largely neutral with a small admixture of partially ionized heavy elements with their free electrons (ionization fraction 10^{-5}). Any wave motion of the magnetic fields in molecular clouds are strongly coupled to the ions. For those waves with $\lambda \gtrsim \lambda_{min}$, the time scale of momentum transfer between ions and neutrals is smaller than the magnetic perturbation time scale and hence neutrals are also coupled to such waves (Arons & Max 1975). For typical magnetic fields of 1 mG near 'dense' regions in star forming clouds and neutral densities of 10^6 cm^{-3} (eg. Johnston, Migenes & Norris 1989), $\lambda_{min} \sim 3 \times 10^{-7}$ pc, which is much smaller than the size of these dense regions (fraction of a parsec). Thus magnetic waves with $\lambda \gtrsim 3 \times 10^{-7}$ pc can exist in dense regions and the characteristic speed (Alfv́en speed) of these waves is determined by the total density (ie ion + neutral density) of the molecular cloud (Arons & Max 1975).

Crutcher (1999) compiled the available sensitive Zeeman measurements of magnetic field strengths in molecular clouds and their neutral densities. Using this data, I estimate the Alfv́en speed V_A (units of cm s^{-1}) in these clouds;

$$V_A = \frac{2B_{los}}{\sqrt{4\pi \mu n_H m_H}}, \tag{1}$$

where n_H is the hydrogen atom density in units of cm^{-3} , $\mu = 1.4$ is the effective mass of an H+He gas with cosmic abundance and m_H is the mass of the hydrogen atom in gm. The measured line-of-sight magnetic field, B_{los}, in units of G, is multiplied by 2 to convert it into total field strength (Crutcher 1999). Fig. 2 shows the estimated Alfv́en speed in the molecular cloud sample taken from Crutcher (1999). The estimated Alfv́en speeds are confined to a narrow range between 0.7 and 4 km s^{-1} with a median value of 1.6 km s^{-1}. This "constancy" of Alfv́en speed was noted earlier and has been understood from models of magnetic confinement of molecular clouds (eg. Moucschovias & Psaltis 1995; Basu 2000).

We now compare the non-thermal velocity dispersion of carbon lines, σ_{NT}, observed from PDRs with Alfv́en speed in molecular clouds. The non-thermal width is obtained by removing the thermal contribution, estimated using the gas temperature T_{PDR} (see Table 1), from the observed CRL width. The non-thermal line widths are plotted in Fig. 2 for the corresponding PDR densities inferred from carbon line modeling. The non-thermal widths have values between 1.6 and 6 km s^{-1}with a median value of 2.9 km s^{-1}. Fig. 2 shows that the non-thermal line widths are almost "constant" over three orders of magnitude in density. The "constancy" of the non-thermal line widths and their magnitudes are similar (less than a factor of 2) to those inferred for Alfv́en waves in molecular clouds.

The gas phase carbon is ionized in PDR and hence is strongly coupled to the magnetic field in these regions. If we consider similar physical parameters in PDRs as in dense molecular regions ($n_H \sim 10^6$ cm^{-3} ; $B \sim 1$ mG) then λ_{min} of $\sim 3 \times 10^{-7}$ pc is at least two orders of magnitude smaller than the typical line-of-sight thickness of the PDR (ie $L_{\|}$). Thus Alfv́en waves with $\lambda \gtrsim \lambda_{min}$ exist in the PDR and here I consider their contribution to the non-thermal width of the observed carbon lines. The amplitude of the velocity of carbon ions, δv, due to these waves is related to the magnetic perturbation amplitude δB through the equation (eg. Arons & Max 1975)

$$\delta v = \frac{\delta B}{\sqrt{4\pi\mu n_H m_H}}. \tag{2}$$

The observed non-thermal velocity dispersion is approximately given by δv. It is usually assumed that $\delta B \sim B$, in that case, the right hand side of Eq. (2) becomes identical to that of Eq. (1). Based on these considerations and the characteristics exhibited by the non-thermal velocity dispersion and Alfv́en speed in molecular clouds (see above) we assume that the velocity dispersion of carbon lines is an estimate of the Alfv́en speed in the PDR.

The observed velocity dispersion is usually scaled by $\sqrt{3}$ to convert it to 3D velocity dispersion. This scaling assumes random magnetic field orientation along line-of-sight and random polarization of Alfv́en waves. Carbon lines are observed from PDRs near UCHs where shocks are present. In such shocked regions only the tangential component of the magnetic field is amplified and the Alfv́en speed associated with this component is scaled by the square root of the density compression ratio (McKee & Zweibel 1995). Hence the scaling factor needed to convert the observed velocity dispersion to a 3D dispersion is uncertain. Direct observation of the Zeeman effect of CRLs may help in determining this factor (see Section 5). Here I note a systematically high value (a factor of 1.8) for the CRL velocity dispersion compared to the Alfv́en speed in molecular clouds, which may be an indication of higher Alfv́en speeds in PDR shocks.

4. Magnetic field in Photo-dissociation regions

The magnetic field strength is obtained using Eq (1) by substituting the estimated non-thermal velocity dispersion of CRL for the Alfv́en speed and using the neutral density obtained from modeling the CRL emission (eg. Roshi et al. 2005b). Field strength values thus obtained are tabulated in Table. 1. These values represent the total magnetic field strength in the PDR. Based on the expected range of the derived physical properties of the PDR (see Section 2), the estimated uncertainty in B is typically a factor of 2.5.

In Fig. 3, we compare the estimated magnetic field with those measured toward molecular clouds. The ordinate of the plot is the number density of H_2 molecules. Here, the estimated field strength values in the PDR are compared with those measured in molecular clouds with similar density. Such a comparison is possible since earlier observations toward molecular clouds show that the magnetic field scales with density ($n_{H_2} \propto \rho^{0.47}$; Crutcher 1999). To produce Fig. 3, the neutral density of the PDR given in Table. 1 is divided by 2 to convert it into number density of $\mathrm{H_2}$. As seen in the figure the estimated magnetic field strengths in the PDR compare well within errors with those measured toward molecular clouds with similar density.

Magnetic field measurements using Zeeman effect of CRLs near 1.4 GHz were attempted toward a few H II regions (Silverglate 1984) of which W48 and S88B are of interest here. The 1.4 GHz CRL emission toward W48 does not originate from the PDR associated with the UCH (Roshi et al. 2005a) and hence a comparison of the upper limit on the field strength obtained by Silverglate (1984) with the estimated value here is not meaningful. Toward S88B, the upper limit for the magnetic field strength obtained is consistent with estimated values given in Table 1. Magnetic field measurements using OH or H I Zeeman effects are available in literature toward a few UCHs listed in Table 1. I compare the field strength given in Table 1 with the results of these observations. Note that OH and H I lines may originate from different spatial locations compared to the CRL forming region. From OH Zeeman observations toward S88B a field strength in the range 0.1 – 0.3 mG was obtained by Sarma et al. (2006 in preparation) consistent with our estimate. Van der Werf & Goss (1990) using H I Zeeman observations measured a peak magnetic field of 0.1 mG in the −45 km s^{-1}component observed toward W3. The CRL LSR velocity is comparable with this velocity and the field strength is consistent with the estimated value. Brogan & Troland (2001) measured a maximum field strength of 0.3 mG toward W49A. They used Zeeman effect of H I to measure the field strength with an angular resolution of 25″. The measured value is about twenty times smaller than the estimated value; possibly because the two tracers (H I and CRL) do not probe the same region in this case.

5. Discussion

As mentioned in Section 2, CRL emission is dominated by stimulated emission for the transitions listed in Table 1. Because of the dominance of stimulated emission, carbon line is detected only from the near side of the UCH. The non-detection from far side of UCH means that the width of CRL is not contributed to by the expansion of the UCH (if the UCH were expanding). Thus the line width has contribution only from thermal and non-thermal motions. The carbon line width may also have contributions from large scale motions such as outflows. However, the similarity of line widths observed from different sources (see Table 1) may indicate that this contribution is small. Thus the field strength estimated in Section 4 may not be affected by such large scale motions. However, presence of any non-magnetic turbulence would affect the estimation of the field strength and hence the values obtained should be considered as upper limits.

The magnetic origin of CRL width can be confirmed by measuring the field strength using Zeeman effect of carbon lines from the PDRs and comparing it with the values estimated in Section 4. If confirmed then multi-frequency CRL observations form another tool to deduce the strength of magnetic fields near star forming regions.

I acknowledge many useful discussions with K. Subramanian, S. Sridhar, A. A. Deshpande, D. Bhattacharya and helpful comments from an anonymous referee.

REFERENCES

Arons, J., Max, C. E., 1975, ApJ, L77

Barrett, A. H., Meeks, M. L., Weinreb, S., 1964, Nature, 202, 475

Basu, S., 2000, ApJ, 540, L106

Brogan, C. L., Troland, T. H., 2001, ApJ, 550, 799

Churchwell, E., 2002, ARA&A, 40, 27

Churchwell, E., Walmsley, C. M., Cesaroni, R., 1990, A&AS, 83, 119

Crutcher, R. M., 1999, ApJ, 520, 706

Garay, G., Lizano, S., Gomez, Y., Brown, R. L., 1998, ApJ, 501, 699

Gomez, Y., et al. , 1998, ApJ, 503, 297

Hollenbach, D. J., Tielens, A. G. G. M., 1997, ARA&A, 35, 179

Johnston, K. J., Migenes, V., Norris, R. P., 1989, ApJ, 341, 847

Kantharia, N. G., Anantharamaiah, K. R., Goss, W. M., 1998, ApJ, 504, 375

Larson, R. B., 1981, MNRAS, 194, 809

McKee, C. F., Zweibel, E. G., 1995, ApJ, 440, 686

MacLow, M. M., in Simulations of magnetohydrodynamic turbulence in astrophysics, eds. T. Passot & E. Falgarone, Lecture Notes in Physics, 614, 182

Morris, M., Zuckerman, B., Turner, B. E., Palmer, P., 1974, ApJ,192, L27

Mouschovias, T. Ch., 1975, Ph.D. thesis, Univ. California, Berkeley

Mouschovias, T. Ch., 1987, Physical processes in interstellar clouds, Eds G. E. Morfill & M. Scholer, D. Reidel publishing company, Dordrecht, p453

Mouschovias, T. Ch., Psaltis, D., 1995, ApJ, 444, L105

Myers, P. C., Goodman, A. A., 1988a, ApJ, 326, L27.

Myers, P. C., Goodman, A. A., 1988b, ApJ, 329, 392.

Natta, A., Walmsley, C. M., Tielens, A. G. G. M., 1994, ApJ, 428, 209

Roshi, D. A., Goss, M. W., Anantharamaiah, K. R., Jeyakumar, S., 2005a, ApJ, 626, 253

Roshi, D. A., et al. 2005b, ApJ, 625, 181

Roshi, D. A., De Pree, C. G., Goss, W. M, Anantharamaiah, K. R., 2006, ApJ, 644, 279

Shu, F. H., Adams, F. C., Lizano, S., 1987, ARA&A, 25, 23

Silverglate, P. R., 1984, ApJ, 279, 694

Troland, T. H., Heiles, C., 1986, ApJ, 301, 339

Vallee, J. P., 1989, A&A, 224, 191

van der Werf, P. P., Goss, W. M., 1990, A&A, 238, 296

Zuckerman, B., Evans, N. J. II, 1974, ApJ, 192, L149

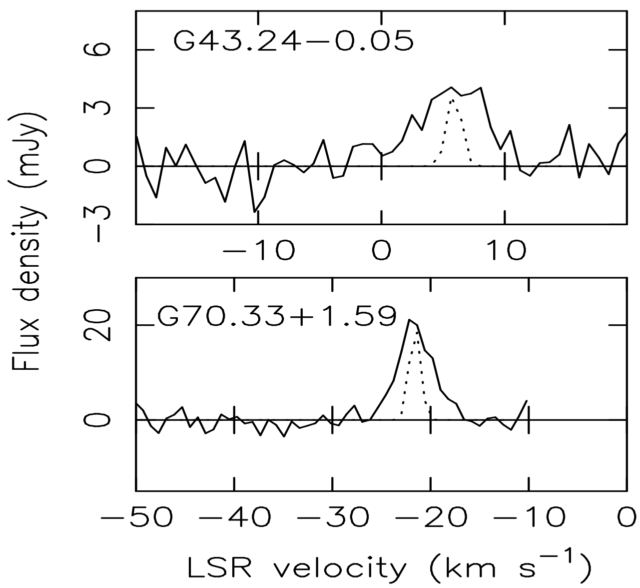

Fig. 1.— Examples of carbon recombination line spectra toward UCHs G43.24−0.05 and G70.33+1.59 observed near 9 GHz (Roshi et al. 2005a). The Gaussian profiles plotted in dotted line correspond to an assumed PDR gas temperature of 1000 K. The large difference between the observed line profiles and the Gaussian curves demonstrates the dominance of non-thermal motions in the PDR. The LSR velocity is with respect to the C89α (9.1779 GHz) transition.

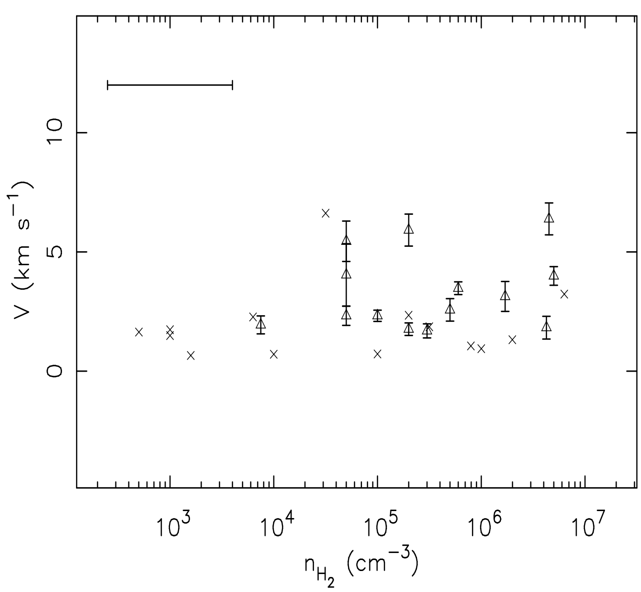

Fig. 2.— Alfv́en speed in molecular clouds (crosses) and non-thermal velocity dispersion of carbon lines (triangles) observed toward PDRs near UCHs are plotted against density in these regions. Alfv́en speeds are estimated from the molecular line data compiled by Crutcher (1999). Errors in the non-thermal velocity dispersion are derived from the uncertainties in the measurements and estimation of the model parameters. The expected range of the estimated densities for the PDR is shown by the horizontal bar. The plot shows that the non-thermal component of the CRL width is "constant" for almost all PDRs and has a median value similar to that of Alfv́en speed in molecular cloud.

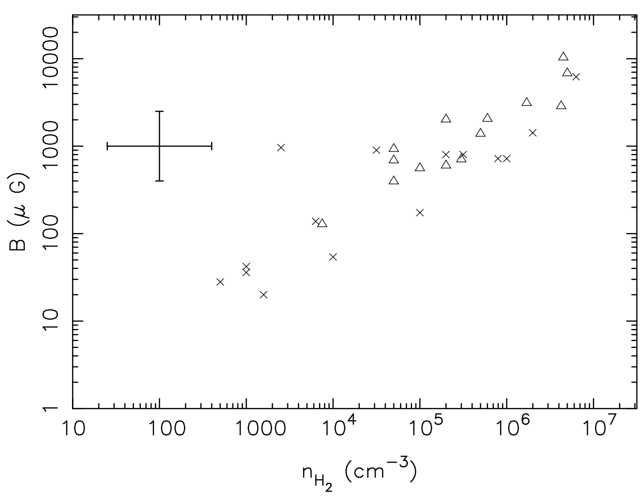

Fig. 3.— Log-log plot of the magnetic field strength vs neutral density. The plot compares the magnetic fields measured in molecular clouds (crosses; data taken from Crutcher 1999) with those estimated using recombination line data (triangles). Comparison is done for similar H_2 densities in the molecular cloud and the PDR. Such a comparison is possible since earlier observations toward molecular clouds show that the magnetic field scales with density (Crutcher 1999). The plot shows that the field strengths estimated using CRL data (see Section. 4) are comparable with those measured in molecular clouds with densities similar to PDR densities. The expected range of density and estimated magnetic field are shown by horizontal and vertical error bars respectively.

Table 1: Carbon recombination line data.

Source name	Transition	ΔV (km s^{-1})	T_{PDR} (K)	n_{C^+} (cm^{-3})	n_H ($\times$ 10^6 cm^{-3})	$L_\parallel$ ($\times$ 10^{-3} pc)	B (mG)	Ref
W48A	C76α	4.5(0.8)	500	2500	8.5	0.3	2.9	1
W49G[a]	C91α	9.5(0.8)	500	3000	10.0	0.1	6.8	2
W49J[a]	C91α	15.1(1.5)	500	2800	9.0	0.4	10.4	2
S88B-east	C92α	4.4(0.3)	600	80	0.4	160.0	0.6	3
S88B-west	C92α	5.6(0.4)	400	40	0.2	220.0	0.6	3
GGD12−15	C92α	4.7(0.7)	330		0.02	130.0	0.1	4
W3A	C168α	5.5(0.9)	100		0.1	50	0.4	5
G32.80+0.19[b]	C89α	7.5(1.3)	500	1000	3.4	1.1	3.1	6
G37.87−0.40[b]	C89α	14.0(1.5)	500	120	0.4	29.0	2.0	6
G43.24−0.05[b]	C89α	6.2(0.9)	500	300	1.0	9.0	1.4	6
G45.12+0.13[b]	C89α	12.9(1.9)	500	40	0.1	124.0	0.9	6
G45.45+0.0[b]	C89α	9.6(2.9)	500	30	0.1	150.0	0.7	6
G70.29+1.60[b]	C89α	8.3(0.5)	500	350	1.2	8.6	2.1	6
G70.33+1.59[b]	C89α	4.2(0.4)	500	170	0.6	25.0	0.7	6

[a] Modeling of carbon line emission for these sources has provided upper limits for n_{C^+}, n_H and lower limits for $L_\parallel$.

[b] The data for these sources are taken from the Arecibo survey. Modeling of carbon line emission for these sources has provided lower limits for n_{C^+}, n_H and upper limits for $L_\parallel$.

References: (1)Roshi et al. (2005a); (2) Roshi et al. (2006); (3) Garay et al. (1998); (4) Gomez et al. (1998); (5) Kantharia et al. (1998); (6) Roshi et al. (2005b).